Development of an Autonomous EV Navigated with GNSS and 5G

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Abstract: Autonomous electric vehicles, the Global Navigation Satellite System (GNSS), and 5G technologies are key drivers of economic, agricultural, and logistics. This paper presents the development of autonomous electric vehicles (AEV) equipped with a GNSS receiver kit for high-precision satellite navigation. The correction for common errors in GNSS systems is sent from a RTK base-station to the moving AEV via a 5G network. The experiment has been designed to let the AEV run in automatic mode to record the position in two different areas with different 4G/5G coverage. In both areas, GNSS positioning in 4G and 5G networks was compared. The experimental results show that network coverage affects the reception accuracy of GNSS positioning and navigation. However, the position discrepancy is not clearly significant due to the speed of 4G and 5G systems.

Keywords: Autonomous electric vehicles, the Global Navigation Satellite System (GNSS), 5G

1. Introduction

Autonomous electric vehicles, the Global Navigation Satellite System (GNSS), and 5G technologies are key drivers of economic, agricultural, and logistics. The integration of GNSS and 5G is a potential technology to provide accurate positioning for autonomous vehicle navigation.

The combination of GNSS and 5G has been studied to provide accurate positioning in various ways. A hybrid 5G RTT (Round-Trip Time) and GNSS positioning in a deep urban canyon was simulated using three-dimensional (3D) city maps to coherently determine the line-of-sight (LoS) conditions of the available satellite and cellular links [1]. A multiple-rate adaptive Kalman filter (MRAKF) for GNSS-5G hybrid positioning with a hybrid sequential fusing scheme significantly improved the positioning accuracy [2]. The integration of GNSS and a novel CO-MWR protocol for device-to-device (D2D) measurement methodology in 5G communication systems improved the measurement efficiency without consuming much more resources than the conventional TWR protocol [3]. A multisensor precision positioning system based on MEMS sensors, 5G NB-IoT communication, and a GNSS receiver with a high update rate was capable of real-time monitoring of the system location and spatial positions [4]. The performance of disseminating the RTK correction information using the Message Queuing Telemetry Transport (MQTT) protocol over 5G caused overheads comparable to the latency increase caused by indirection [5]. A physical-layer abstraction of GNSS and 5G ranging observables was proposed to ease the complexity of the resulting system-level simulations [6]. Most of these studies are simulation-based, and the NLoS bias with 3D city maps, as well as the use or mitigation of NLoS or outlier observables within the hybrid positioning algorithm, is left to the next challenge.

For precise vehicle self-localization systems for autonomous driving, sensor fusion techniques have been proposed. The lane detection resulted from on-board cameras was integrated with the GNSS/INS system in order to improve the positioning errors [7]. Unfortunately, 5G networks are not available at that time. The integration of a tactical-grade Inertial Navigation Unit (IMU) and an accurate GNSS receiver in RTK (Real-Time Kinematic) mode, and the employment of a 5G radio-modem to compensate for any signal loss or damage, are suitable for a custom drone whose mission consists of reproducing typical cinematographic shots in unstructured environments [8]. A GNSS-free emergency location-based service (LBS) using fog computing in a 5G-enabled IoV when GNSS failure can achieve high-precision location estimation [9]. This is simulation based. A 5G positioning simulation experiment scheme including scene generation, signal propagation simulation, and position estimation has been preliminary studied for integrated navigation of inertial measurement units (IMU) and 5G positioning [10]. Since the channel simulator is at a relatively basic level, it is a challenge to effectively simulate the impact of carrier bandwidth on positioning.

This paper presents the development of a small autonomous electric vehicle (AEV) for delivery purpose. The AEV equipped with a GNSS receiver kit for high-precision satellite navigation. The correction for common errors in GNSS systems is sent from a RTK base-station to the moving AEV via a 5G network. The real tests were performed to evaluate GNSS satellite signal reception over 5G networks.

2. Preliminaries

2.1 GNSS

GNSS (Global Navigation Satellite System) is a satellite navigation system. It uses an electronic device as a receiver to perform positional processing where the receiver device is located. This technology is gaining popularity in survey and research applications. Currently, several satellite navigation systems have been developed, such as GPS (USA), GLONASS (Russia), Galileo (Europe), BeiDou (China), QZSS (Japan), SBAS, etc.

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To support maximum efficiency, many countries have applied this GNSS technology by creating a network of coordinates, level, and time-standard permanent continuous satellite receivers, or GNSS CORS NETWORK (GNSS Continuously Operating Reference Station Network). This permanent continuous satellite receiver reference station will send the corrective signals in a network fashion. This enables highly accurate positional processing in a short time.

2.2 RTK

Real-time kinematic positioning (RTK) is the application of surveying to correct for common errors in current GNSS systems, with which users can obtain centimeter-level accuracy of the position in real-time scenarios. It uses measurements of the phase of the GNSS signal carrier wave in addition to the information content of the signal and relies on a single reference station or interpolated virtual station to provide real-time corrections.

RTK has traditionally been used in mobile mapping systems, precise vehicle navigation, construction machine control, and precision agriculture.

2.3 5G

The 5G network is a telecommunications innovation that has transformed the paradigm of human-centric communication to machine-centric communication, fully aligned with the digital transformation of society as a driving force. Pushing big data collection combined with artificial intelligence (AI) computing and machine learning, 5G networks are key to increasing the potential and effectiveness of human life in terms of social, economic, and quality of life.

5G is used in three sets of frequencies: low band in the 700 MHz range; mid-band (Sub 6) in the 3 GHz band; and mmWave in the 26-28 GHz range. Each frequency band is suitable for different applications. With this feature, 5G offers data rates comparable to fixed internet fiber optic networks, and it is more flexible than 4G.

3. Autonomous EV Development

The prototype autonomous EV (AEV) navigated with GNSS and 5G consists of the development of a body, a vehicle control, sensor fusion, lane detection and keeping, situation awareness, environment status logging (VDO logging), GNSS positioning, and a 5G router.

3.1 Body

The AEV shown in Fig. 1 is 54.0 cm wide, 77.9 cm long, and 35.0 cm high, and weighs 8.66 kg. Four layers of components are assembled. The two LiPo batteries, the motor drive, and the power controller are arranged in two bottom layers. The next upper layer consists of a microcontroller, a Pantai GNSS, a vehicle controller, and a DC-to-DC step down. The top layer consists of cameras and sensors, a 5G router, GPS, and another DC-to-DC step down.

3.2 Vehicle Control

The vehicle controller overview is shown in Figure 3. Model-Based Design (MBD) on MATLAB Simulink is the main platform for sensor fusion and vehicle control. An auto steering gear, Pixhawk 4, is installed to work as shown in Fig. 3. Pixhawk 4 can control the

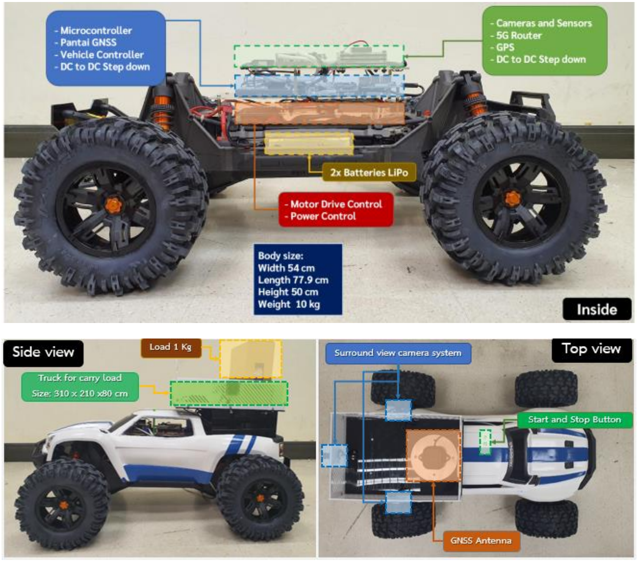

Fig.1 The prototype autonomous EV (AEV) body.

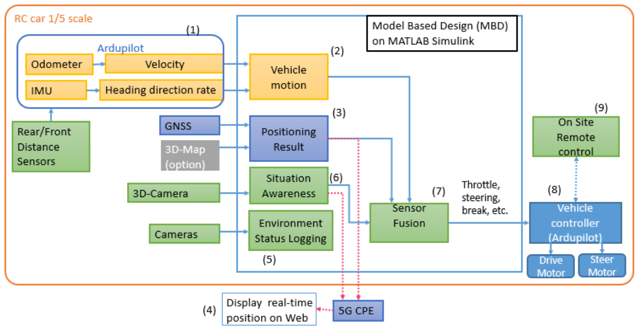

Fig. 2 The prototype autonomous EV (AEV) control.

movement of vehicles to accelerate, slow down, move forward, backward, turn, or any other pattern from one point to another, following a specified path. There are two main types of vehicle controls: manual driving and autonomous driving. Manual driving has been designed by inserting a basic safety system into the car. The car is able to stop itself when there are obstacles within the specified distance. The nature of the car's self-stop is not a sudden brake, but there will be a gradual speed reduction until stop. Even in manual driving mode, the sensor fusion status must be checked for safety. Safety must be taken into account in terms of system design for autonomous driving control. Therefore, system design requires many variables to be involved. The key components that affect the system are image processing and sensor fusion, which are explained in detail in the next section.

3.3 Sensor Fusion

Sensor fusion is a multi-sensor merging process, as shown in Fig. 2, to calculate the detected parameters together to achieve realistic results. The most accurate control signal can be generated for the vehicle controller module. The parameters that are detected in the system come from the following modules:

- Vehicle motion combines the IMU (Inertial Measurement unit), odometer, and ultrasonic sensor provided by the Ardupilot

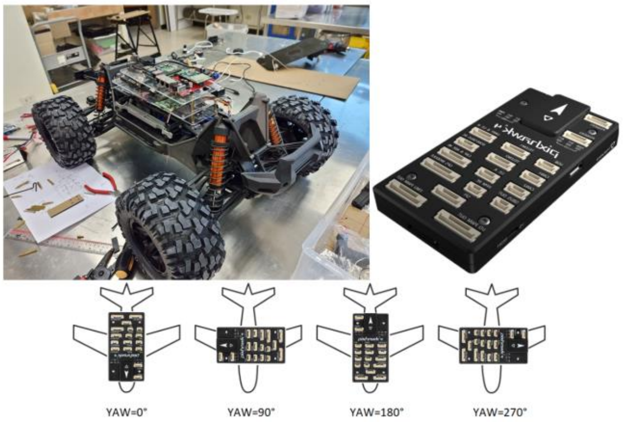

Fig. 3 Auto steering gear installation.

module to obtain vehicle motion parameters.
- The positioning result module compensates for the errors from the GNSS and provides accurate position answers.
- Situation awareness uses the image from the 3D camera to detect the road lane and the distance from the ultrasonic to detect the obstacles.

3.4 Lane Detection and Keeping

The Python program on the car's main computer is used to process images for lane detection. The control information is then sent to the flight control via serial interface to calculate with the sensor fusion system so that the car can be driven to the specified coordinates. The image processing starts with receiving the image from the camera and then forwarding it to the automatic color and light adjustment section to reduce the effect of the color and light interpretation of each sequence from the different time periods of system testing. Then, the thresholding method is applied to separate the lane lines from the background image. The next step is finding edges with the Canny edge detection and lines with the Hough Transform method.

3.5 Environment Status Logging

The environment status logging module in Fig. 2 is a vehicle surveillance camera system for recording and displaying a 360-degree view of the vehicle. This VDO logging can be applied to various driving assistance systems, such as avoiding obstacles or parking assistant. The operation of the vehicle environment status logging consists of acquiring the image from the four cameras, processing the image on the processor (Raspberry Pi), and displaying it on the monitor as shown in Fig. 3.

3.6 GNSS positioning

Pantai GNSS is a receiver device that can receive signals from GPS/GLONASS/BeiDou/Galileo/QZSS/CORS RTK/MADOCA satellite networks or other channels [11]. It has a feature that allows it to turn itself into a base station, which collects a single reference for the receiver over 4G and 5G networks. However, several uncertainties affect the accuracy of position values. An Extended

Fig. 4 Camera system for environment status logging.

Kalman Filter (EKF) is used to improve the accuracy of vehicle positioning in conjunction with the Pantai GNSS. This correct position will be directed to the Pixhawk 4 for maneuvering the vehicle to the specified position.

3.7 5G router

The GNSS receivers must correct for errors brought on by distortion in the GNSS signal's route owing to atmospheric circumstances. The Real-Time Kinematics (RTK) technique makes use of terrestrial reference stations that continuously assess the strength of GNSS signals and offer data that GNSS receivers nearby can use to correct for such errors. Here, the 5G router in the vehicle is used to receive the correction information from the RTK station.

4. Experimental Results

This section presents an evaluation of GNSS satellite signal reception over 5G networks compared to 4G. The experiment has been designed to install a Pantai GNSS device, which is represented as a base station on the top of the building in Fig.5, and let the AEV run in automatic mode to record the position in two different areas with different 4G/5G coverage as follows.

4.1 Test areas

There are two test areas: #1 PSU lake and #2 PSU running field. Test area #1 is 1.3 kilometers long. Test area #2 is 400 meters long. Both areas have 4G/5G mobile network coverage as shown in Fig. 5. Obviously, test area #2 has perfect 4G/5G coverage, whereas test area #1 is the worst. Although there is low 5G coverage, a mobile phone running in 5G mode can detect 5G in test area #1. From this point of view, we can use it as a condition for analyzing the evaluation results.

Fig. 5 4G/5G mobile network coverage (cdn.nperf.com/en/map).

4.2 Test areas

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4.3 Test areas #1

In the experiment, the AEV was moved in automatic mode to record the location of the vehicle moving around the test area. The reception of the GNSS satellite network is evaluated to compare 5G and 4G. In each iteration, the position obtained directly from the Pantai GNSS module is recorded and compared to that obtained from the EKF algorithm deployed to compensate for the uncertainty of the position value obtained from the Pantai GNSS module. Fig.6 shows the weather conditions while testing areas #1. The experiment was conducted in five rounds, each round covering a distance of 1.3 kilometers. Figs. 7 and 8 show GNSS satellite network reception errors with 4G and 5G, respectively. The purple line is the position obtained directly from the Pantai GNSS module, and the blue line is the position value obtained from the EKF algorithm.

The data from five rounds of experiments in test area #1 were presented as shown in Table 1. The data shown in the table cannot be directly compared lap-by-lap because the trials are conducted separately between 4G and 5G in each cycle, but can be compared as a whole. From the information shown in Table 1, there are observations as follows:

- The Pantai module position error was 5.18% minimum and 16.81% maximum in the 5G case, and 3.12% minimum and 6.46% maximum in the 4G case.
- The EKF algorithm calculated a position value with a minimum tolerance of 1.56% and a maximum tolerance of 1.78% in the 5G case, and a minimum tolerance of 1.39% and a maximum


Fig. 6 Weather conditions while testing areas #1.


Fig. 7 4G Round 1: (619 samples) EKF error = 3.55% Pantai error= 6.46%.


Fig. 8 5G Round 1: (618 samples) EKF error = 1.78% Pantai error= 5.18%.

Table 1: The reception of the GNSS satellite network is evaluated to compare 5G and 4G in test area #1.

	Position error 4G (%) case		Position error 5G (%) case	
Iteration	EKF	Pantai	EKF	Pantai
Round 1	55.3	46.6	78.1	18.5
Round 2	39.1	12.3	62.1	36.5
Round 3	72.1	30.4	61.1	28.6
Round 4	69.1	92.4	57.1	81.16
Round 5	48.1	74.5	56.1	65.15
Average	1.966	4.908	1.628	9.856

Table 2: The reception of the GNSS satellite network is evaluated to compare 5G and 4G in test area #2.

	Position error 4G (%) case		Position error 5G (%) case	
Iteration	EKF	Pantai	EKF	Pantai
Round 1	89.12	21.13	53.0	60.1
Round 2	57.4	57.4	49.1	99.0
Round 3	52.0	52.0	00.0	62.2
Round 4	00.0	48.0	51.0	02.2
Round 5	44.0	00.0	00.0	53.0
Average	3.684	3.756	0.506	1.552

tolerance of 3.55% in the 4G case.

- The position values obtained from the EKF algorithm were more accurate than those obtained directly from the Pantai module in both 4G and 5G cases.
- The insignificant difference is due to the speed of 4G and 5G systems, as evidenced by some test cases using 5G networks.
- Differences in performance between 4G and 5G may be due to network coverage, as the 4G network covers more than the 5G network, as shown in Fig. 5.

4.4 Test areas #2

The same experiment was repeated in test area #2. Fig.9 shows the weather conditions while testing areas #2. The experiment was conducted in five rounds, each round covering a distance of 1.3 kilometers. Figs. 10 and 11 show GNSS satellite network reception errors with 4G and 5G, respectively. The purple line is the position obtained directly from the Pantai GNSS module, and the blue line is the position value obtained from the EKF algorithm.

The data from five rounds of experiments in test area #2 were presented as shown in Table 2. The data shown in the table cannot be directly compared lap-by-lap because the trials are conducted separately between 4G and 5G in each cycle, but can be compared as a whole. From the information shown in Table 2, there are observations as follows:

- The Pantai module position error was 0.53% minimum and 2.62% maximum in the 5G case, and 0.00% minimum and 13.21% maximum in the 4G case.
- The EKF algorithm calculated a position value with a minimum tolerance of 0.00% and a maximum tolerance of 1.49% in the 5G case, and a minimum tolerance of 0.00% and a maximum tolerance of 12.89% in the 4G case.
- The position values obtained from the EKF algorithm were more accurate than those obtained directly from the Pantai module in both 4G and 5G cases.
- In 5G cases, location errors are slightly better than on 4G, which may be due to network coverage. Because in test area #2, the 5G network covers more than test area #1, based on the information shown in Figure 5. However, the location error is not clearly significant because of the speed of 4G and 5G systems.

5. Conclusions

This paper presents the development of autonomous electric vehicles (AEV) equipped with a GNSS receiver kit for high-precision satellite navigation. The correction for common errors in GNSS systems is sent from a RTK base-station to the moving AEV via a 5G network. The experiment has been designed to let the AEV run in automatic mode to record the position in two different test areas with different 4G/5G coverage. Network coverage affects the reception of GNSS signals for accurate positioning and navigation. However, the position error is not clearly significant due to the speed of 4G and 5G systems. Using the EKF algorithm can reduce the instability of the GNSS signals received by the Pantai GNSS module.

Fig. 9 Weather conditions while testing areas #2.

Fig. 10 4G Round 1: (318 samples) EKF error = 12.89% Pantai error= 13.21%.

Fig. 11 5G Round 1: (188 samples) EKF error = 0.53% Pantai error= 1.60%.

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Acknowledgments

This work has been supported by Faculty of Engineering, Prince of Songkla University and Geo- Informatics and Space Technology Development Agency (GISTDA).

